Techniques for Measuring Substrate Embeddedness

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Complexity	***Environmental Value***	***Cost***
Low Moderate High	Low Moderate High	Low Moderate High

OVERVIEW

The degree to which fine sediments surround coarse substrates on the surface of a streambed is referred to as embeddedness. Although the term and its measurement were initially developed to address habitat space for juvenile steelhead trout, embeddedness measures have been used to assess fish spawning and macroinvertebrate habitat, as well as substrate mobility (Figure 1). Embeddedness is used as a water quality indicator in some areas.

No publication provides a comprehensive description of embeddedness, and the sampling methodology is far from standardized. This technical note represents a compendium of embeddedness measurement techniques, compiled from journal papers, agency reports, and personal files of those involved in the development of the techniques and their applications. This technical note also documents the definitions and usage of the term "embeddedness," describes the development of embeddedness measurement techniques, provides guidelines for the application of measurement techniques, and summarizes the existing literature. The information presented here is derived from a study by Sylte (2002) and accompanies an assessment of the methods reported by Sylte and Fischenich (in preparation).

EMBEDDEDNESS SIGNIFICANCE

The character of stream substrates is important to both physical and biological stream functions. Physically, as stream substrates become more embedded, the interstitial space between particles is reduced, thus effectively reducing streambed roughness and altering channel bedform and hydraulics. Streambed and substrate mobility can be substantially affected by the quantity and characteristics of the fine material (Wilcock 1998). In addition, without periodic mobilization of fine sediments from the coarse bed material, deposited fines eventually clog interstitial voids (Kondolf and Wilcock 1996, Osmundson and Scheer 1998).

Figure 1. Interstitial spaces in streambed substrate are important habitats for many aquatic organisms

Biologically, permeability and interparticle dissolved oxygen can be negatively affected, which directly impacts spawning for many fish

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species. Increases in embeddedness levels decrease the space between particles and limit the available area and cover for small fish, macroinvertebrates, and periphyton. Shifts to finer materials in particle size distributions can alter biotic communities by reducing species diversity and density (Lenat, Penrose, and Eagleson 1981). An increase in fine sediment reduces geometric mean particle size and gravel permeability andleads to lower dissolved oxygen levels in pore water (Chapman 1988). Thermal attenuation, decomposition, and nutrient transport also depend on percolation and the extent of sediment deposition in interstitial spaces among gravel particles (Young, Hubert, and Wesche 1990; Bjornn and Reiser 1991). Substrate permeability can be reduced by deposition of fine sediment in spawning gravels (Moring 1982; Platts et al. 1989, Rinne 1990). This in turn results in the reduction of embryo survival, fry emergence, and fry size (Tappel and Bjornn 1983; Young, Hubert, and Wesche 1990). It also impacts regeneration and living space for macroinvertebrates (Merrit and Cummins 1984).

EMBEDDEDNESS DEFINED

Many embeddedness definitions exist in the literature because the term has been applied to characterize a variety of impacts and conditions. The following is a summary:

- Kelley and Dettman (1980): "the degree to which cobble larger than 45-mm diameter is embedded in sand."
- Platts, Megahan, and Minshall (1983) and Fitzpatrick et al. (1998): "the degree that the larger particles (e.g., boulder, rubble, gravel) are surrounded or covered by fine sediment."
- Burns (1984) and Burns and Edwards (1985): "the amount of fine sediment that is deposited in the interstices between larger stream substrate particles."
- MacDonald, Smart, and Wissmar (1991): "the extent to which larger particles are buried by fine sediment."
- Osmundson and Scheer (1998): "the 'depth to embeddedness' is the distance from the top of the rocks on the bed surface down to the top of the layer of fines in which the cobbles are embedded."
- Bain and Stevenson (1999) slightly modify Platts, Megahan, and Minshall (1983) by defining fine sediment as sand, silt, or clay.
- Bunte and Abt (2001): "the position of a large particle relative to the plane of the bed when that particle is partially buried in finer sediment."
- Environmental Protection Agency (EPA) Environmental Monitoring and Assessment Program (EMAP) protocol: Lazorchak, Klemm, and Peck (1998); Kaufmann et al. (1999); Peck, Lazorchak, and Klemm (2000). Embeddedness is referenced to Platts, Megahan, and Minshall (1983).
- Davis et al. (2001): "qualitative estimate of the percent of substratum particles covered by fine materials."

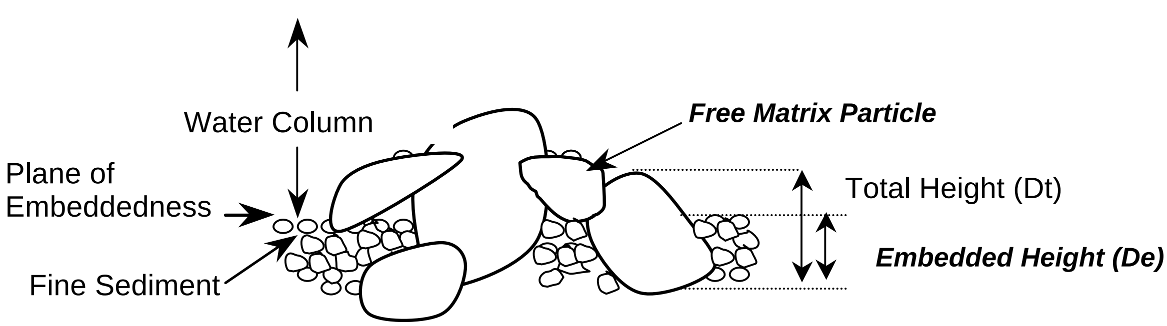

Figure 2. Schematic representation of embeddedness

As ambiguous as the term "embeddedness" may be, no other terms have been developed to describe the phenomenon of fine sediments filling the interstices between coarser sediments on the streambed. Embeddedness is discussed conceptually more than it is measured, leading to two misconceptions about the term; namely, (1) embeddedness is a direct measure of fine sediment quantity (volume), and (2) embeddedness addresses substrate mobility. With the current methodology, both concepts are inaccurate portrayals of embeddedness and what it measures.

Embeddedness measures the degree to which larger particles are covered with finer particles – a length term representing a volume of fines surrounding coarser substrates, which is often placed in a relative proportion to rock height in the plane of embeddedness (Figure 2). Moreover, "fines" are commonly not defined even though the nature and degree of impact depend upon the size and character of the sediments filling interstitial voids.

LITERATURE REVIEW: EMBEDDEDNESS MEASUREMENT METHODS

Klamt (1976) and Kelley and Dettman (1980) introduced the concept of embeddedness. Klamt estimated the degree to which key rocks or dominant rocks in streams were embedded by using 25, 50, and 75 percent embeddedness levels. Kelley and Dettman (1980) focused on juvenile steelhead rearing habitat and quantified the depth of sand particles surrounding cobble-sized substrate in "glide," "glide/riffle," and "riffle" habitat units. Several techniques have since been developed to measure or characterize embeddedness.

The following paragraphs describe existing methods presented in the literature. Care is taken to maintain the authors' original wording. Tables 1 and 2 summarize the various methods described in this section. Supplemental detail, errors, and inconsistencies in the documentation are noted by footnotes in an effort to reduce future confusion and improve subsequent embeddedness studies and publications.

Platts/Bain -- Visual Method

According to Platts, Megahan, and Minshall (1983), embeddedness rates the degree to which larger particles (boulder, rubble [sic], gravel) are surrounded or covered by fine sediment (Table 3). The ratings are an estimate of how much of the surface area of the larger sized particles is covered by fine sediment. Platts, Megahan, and Minshall (1983) reported that the 95-percent confidence interval around the mean embeddedness was low (± 5.4 %) with year-to-year precision good and accuracy fair.[3]

Bain and Stevenson (1999) used the same technique but added guidance for sample location and replication. Descriptions instead of numbers are used as ratings (negligible, low, moderate, high, and very high corresponding to Platts, Megahan, and Minshall (1983) ratings of 5, 4, 3, 2, 1, respectively). Bain and Stevenson (1999) also specifically defined fines as clay, silt, and sand (materials less than 2 mm in diameter). Embeddedness is classified in five or more representative habitats (e.g., riffle, run, pool) on the thalweg or at mid-stream locations.[4] They further stated that embeddedness should be assessed after substrate sizes have been described in qualitative or quantitative terms, and observers should be experienced.
Bain and Stevenson (1999) reported the technique as simple to conduct and meant to

[3] This publication provides a sound foundation of sampling design for evaluating stream conditions. Guidance for sampling is primarily dependent on the study question and acceptable level of accuracy and repeatability. Two misprints exist in the embeddedness section. First, in the first paragraph describing embeddedness, biotic productivity is said to "decrease" with "decreasing embeddedness," when in fact they are inversely related – as embeddedness increases (more fines), biotic productivity decreases. The authors meant a proportional relationship between embeddedness "rating" and biotic productivity (Table 2). If "embeddedness rating" were used instead of "embeddedness," the statement would be accurate. Second, in Figure 2.11 (Platts, Megahan, and Minshall (1983), the rating should be 4 instead of 2 for the illustration. These two misprints may confuse those that are initially exploring embeddedness by reading this document.

[4] Presumably mid-stream if thalweg is undefined.

approximate the condition of the substrate relative to fine sediment impacts. They stated that visual assessment of embeddedness is not highly accurate but is often sufficient to meet many management evaluation needs because the significance of a specific level of embeddedness for individual fish species is poorly quantified.

Davis et al. (2001) provided a discussion of embeddedness, presumably based on the original Platts, Megahan, and Minshall (1983) publication because of the terminology and use of stratifications. However, Davis et al. (2001) suggested uneven class sizes (one size class of 5 and 20, and three size classes of 25 percent). Embeddedness is described as a qualitative estimate of the percent of substratum particles covered by fine materials. For each stone, the intermediate axis measurement and percent of the particle embedded (in 25-percent increments) are recorded and described by mean, standard deviation, and coefficient of variation.

Table 1. Summary of embeddedness methods

METHOD	MODE	SAMPLE NO.	SAMPLE LOCATION	DESCRIPTION
Platts/Bain	Visual	General sample design guidance; no specifics for embeddedness	Thalweg or mid-channel (Bain and Stevenson 1999)	Embeddedness Classes of 0-5, 5-25, 25-50, 50-75, 75-100
EPA EMAP	Visual	55	Five estimates at 11 cross-sections	10-cm sampling area at 0, 25, 50, 75, 100 percent of cross-sectional width
Burns	Measured	100-400 individual particles, depending on desired standard deviation from the mean	Specific fish habitat criteria	Random 60-cm hoop toss; specific depth and velocity criteria, hoops tossed until sample particle number is attained
BSK (Burns, Skille, and King)	Measured	Typically, 20 random hoops. Recommend statistically determined sample size. Three hoops per transect typically result in ≅100 individuals sampled per transect	Typically, transects spanning bank-to-bank for a reach length of ≅ 20 times the average stream width	Skille and King (1989) modified Burns (1984). Focused on stream-related questions, improved statistics by averaging individuals within the hoop and then averaging for the transect
USFWS	Measured	20 measurements per site	Minimum of 1 run and riffle per site, specific depth and velocity criteria wading parallel to shoreline	Measures depth to embeddedness (DTE) (protrusion); 20 DTE are divided by median rock width for that site, then averaged for the reach
USGS NAWQA	Visual	5 gravel-to boulder-sized substrates are examined at three transects	Not specified	Percentage (nearest 10 percent) of embedded depth per particle is averaged

Table 2. Summary of BSK embeddedness computational methods

COMPUTATIONAL METHOD	EQUATION	DESCRIPTION
BSK-orig	$100^*(\sum De/\sum Dt)$	One of the original computation forms. Free matrix particles (De = 0) are not counted. This form is also shown in MacDonald, Smart, and Wissmar (1991) and Bunte and Abt (2001).
BSK-n	100*(S De/Dt)/n	Modified computational form utilized by Potyondy (1988). Initially developed and used on the Payette National Forest.[5] Depending on "n," total rock count, free matrix particles can be considered, free matrix particles were not counted in Potyondy's n value but are in this analysis.[6]
BSK-wt	% weighted = (hoop area in fines (%) x 100 + remaining area (%) x % embeddedness)/100	Skille and King (1989) modified the original Burns (1984) equation to address large portions of fines within the hoop that are not counted in particle measurements; portions of the hoop in excess of 10 percent fines are weighted into the equation as 100 percent embedded

Table 3. Embeddedness rating for gravel, rubble, and boulder particles (Platts, Megahan, and Minshall 1983)

RATING	RATING DESCRIPTION
5	< 5 percent of surface covered by fine sediment
4	5 to 25 percent of surface covered by fine sediment
3	25 to 50 percent of surface covered by fine sediment
2	50 to 75 percent of their surface covered by fine sediment
1	> 75 percent of surface covered by fine sediment

Presumably stone measurements are conducted in accord with the Wolman pebble count procedure, but this is unclear. This may imply that embeddedness is measured, but a visual estimation is assumed because no explanation is given for factors such as embeddedness plane and rock height.

EPA EMAP – Visual Method

Three recent EPA EMAP documents provide a methodology for embeddedness determination (Lazorchak, Klemm, and Peck 1998; Kaufmann et al. 1999; Peck, Lazorchak, and Klemm 2000). The embeddedness technique is the same in each. EMAP procedures improve upon the embeddedness methodology in the

[5] Personal communication, 7 August 2002, Mr. Rodger Nelson, Fisheries Biologist, Payette National Forest, McCall, ID.

[6] Statistical procedure suggests summing the individuals in both the numerator and denominator before applying the ratio (e.g., $\sum De/\sum Dt$), rather than summing the individual ratios (e.g., $\sum(De/Dt)$). Results can differ between the two methods and summing the individuals before applying the ratio reduces the effect, or skewness, created by outliers in the data (Cochran 1977).

EPA rapid bioasessment protocol.[7] According to the manuals, Wolman (1954); Bain, Finn, and Booke (1985); Platts, Megahan, and Minshall (1983); and Plafkin et al. (1989) were used as the basis for this methodology.

In the EMAP protocol, substrate size and embeddedness are evaluated at 11 cross-sections spaced at intervals of four times the channel width. This means that a variety of geomorphic features, including pools and riffles, may be sampled. For the embeddedness portion of the protocol, particles larger than sand are visually examined for surface stains, markings, and algal coatings to estimate embeddedness of all particles in a 10-cm-diameter circle surrounding the sampling point. If the sampling point falls on a stone >10 cm in diameter, embeddedness is also evaluated for that stone.[5] Each cross section has five sampling points - at 0, 25, 50, 75, and 100 percent of the wetted channel width. Embeddedness is defined as the fraction of a particle's surface that is surrounded by (embedded in) sand or finer sediments on the stream bottom. Embeddedness of homogeneous sand, silt, clay, and/or muck is 100 percent; bedrock and hardpan are embedded 0 percent. Embeddedness values are averaged to describe the subject reach.

According to Kaufman,[5] research has led EMAP developers to rely less on embeddedness and more on substrate size fraction estimates. These are taken from modified Wolman (1954) pebble counts obtained at 105 systematically spaced locations on the stream bottom. Percent sand and fines (e.g., percent substrate <2 mm) is highly correlated with embeddedness. Kaufman [5] stresses that when using the EMAP field procedures to estimate substrate characteristics of a stream reach, the length of the sample reach, the number of sampling positions, and the systematic spacing of the locations are just as important as the actual procedures for estimating embeddedness at a single point.[8]

CURRENT MEASUREMENT METHODS

Burns (1984) and Burns and Edwards (1985) essentially developed the embeddedness measurement method employed today. Skille and King (1989) later advanced the technique to apply to stream analysis beyond fish habitat and strengthened statistical rigor of the analysis. However, this work has not been published. Although Skille and King (1989) modified and improved Burns (1984), portions of both forms appear in summary publications such as MacDonald, Smart, and Wissmar (1991), Bunte and Apt (2001), and Gebhards (2002).

Burns Method (Burns and Edwards 1985)

Chapman and McLeod (1987) provided a comprehensive review of method development prior to 1987, which is paraphrased in the following two paragraphs.

Burns (1984) used embeddedness level to refer to the proportion of an individual matrix particle surrounded by fine sediment.[9] The size of matrix particles considered was 4.5 to 30.0 cm in greatest diameter, and fine sediment was defined as particles less than 6.3 mm diameter. Burns and Edwards (1985) calculated the proportion by dividing the embedded depth by the total depth of rock lying perpendicular to the embeddedness plane (Figure 2). According to Burns (1984), the population of single-matrix particles must be sampled to characterize substrate conditions. Burns (1984) treated an embeddedness measurement made for one rock as one observation. He used a 60-cm-diameter steel hoop to define particles in the substrate to be measured, a 30-cm-transparent ruler to measure particle dimensions, and a float and stopwatch to measure water velocity.

Whereas Kelley and Dettman (1980) used a random-toss method to quantify embeddedness for general stream condition, Burns (1984) attempted to reduce variability by targeting specific strata within various streams.

[7] Personal communication, 10 October 2001, Mr. P. R. Kaufmann, Research Physical Scientist, U.S. Environmental Protection Agency, Western Ecology Division, Corvallis, Oregon.
[8] This method can be performed very quickly, typically taking 5 to 10 min per transect.

[9] The choice of the word "matrix" to describe these particles differs from geomorphic literature in which "matrix" describes finer sediments and "framework" addresses larger particles resting in or within the matrix particles (Thorne, Bathurst, and Hey 1987).

These sites had a tranquil surface flow over a cobble bottom suited for winter cover selection by overwintering juvenile salmonids. The site had to meet specific depth and velocity criteria (e.g., float time across the hoop diameter: 0.9 to 2.5 sec; water depth: 15 to 45 cm.).

Burns and Edwards (1985) stated that extensive data acquisition is necessary for the proper evaluation of the relative impact to fish habitat from human-caused sedimentation. According to Burns (1984), inter-mean differences of 12 to 18 percent for 100 particles could be detected, but 400 samples would be necessary to detect inter-mean differences of about 5 percent. The following numbered paragraphs more clearly describe the Burns methodology.

1. Embeddedness is measured on single matrix particles, and the entire population is averaged. For each sampled particle, the depth of embeddedness (to the nearest mm) is divided by the particle height (Figure 2).[10]

2. Particles lying inside a 60-cm-diameter steel hoop thrown randomly into specific habitat units are sampled. Particles with ≥ 50 percent of their surface lying within the hoop are counted. The hoop determines particles to be measured. Hoops are thrown into the specified unit until measurements have been taken on at least 100 particles. Although the count may exceed 100, all particles are measured in the last hoop. Typically, 3 to 4 hoops constitute a sample of 100 particles.

3. Float time across the hoop diameter should be between 0.9 and 2.5 seconds. Water depth must be 15 to 45 cm, and the hoop must not lie in an eddy caused by a pool or large boulder.[11]

4. Particles in the hoop should not all be less than 4.5 cm or greater than 30 cm.[12]

5. Sampling requires a 30-cm transparent ruler, graduated in mm, to measure water depth and the largest axis of particles in the hoop. A float and stopwatch are used to measure water velocity, and a steel pry bar is necessary to dislodge some substrates.[13] A transparent ruler is affixed to a Plexiglas measuring frame hinged at right angles (Figure 3).[14]

6. The procedure requires the sampler to begin at one side of the hoop and work across it until each free matrix particle is measured and discarded. Embeddedness of these particles by definition is zero, and therefore they are not counted unless the total rock count is included in the computational method.[15]

7. Starting back across the hoop, embedded particles are systematically removed. Rocks are generally picked up with the right hand and grasped with the thumb and fingers at plane of embeddedness. The particle is rotated so that the embedded portion is to the left. An index finger is placed on the side away from the eye, and the plane of embeddedness is held against one plate of the plexiglass frame and measured (Figure 3).

[10] Burns and Edwards (1985) modified the Burns (1984) technique, which measured the longest diameter perpendicular to the plane of embeddedness. Burns and Edwards (1985) stated that this difference might lead to higher means in the data.

[11] Velocity and depth address criteria for adequate fish habitat. If these conditions are not met, the hoop is tossed again.

[12] Some guidelines advise tossing the hoop again if desired conditions are not met. Some investigators state that the hoop should never be re-tossed because it introduces bias (see footnote 18). On the Payette National Forest at McCall, Idaho, crews are instructed to ignore particles larger than 6.3 mm and smaller than 45 mm and to remove particles larger than 300 mm from within the hoop.[3]

[13] Greatest particle diameter and a-axis of free matrix particles are measured, but no details are provided for use of these measurements. The a-axis length was perhaps collected for future development purposes and characterization of particle size. However, the Payette National Forest uses this dimension to ensure that measured particles fall within the specified size range and for recording in place of the Dt dimension for unembedded particles.[3]

[14] The frame is recommended by Potyondy (personal communication, 10 July 2001, Mr. J. Potyondy, hydrologist, USFS Rocky Mountain Experiment Station, Fort Collins, CO) and was proven very useful in this analysis.

[15] Free matrix particles can be counted by other computational methods discussed in the companion technical report.

Figure 3. Using the plexiglass measuring frame

Burns and Edwards (1985) recognized that misalignment and parallax were considered error sources; misalignment results in random error, whereas parallax is a source of systematic error. Neither was judged to be a significant source of bias for comparison of relative values. Every particle exposed to the water column and meeting site criteria was measured until only a plane of particles >30 cm and/or < 4.5 cm diameter remained.[16]

BSK Method – Burns Method, Modified by Skille and King (1989)

According to Skille and King (1989), water quality monitoring and the need to quantify stream sedimentation related to non-point sources were growing concerns in Idaho during the late 1980s. Cobble embeddedness was a parameter common to many USDA Forest Service (USFS) monitoring efforts, and the Idaho Division of Environmental Quality was becoming involved in land management studies relative to stream sediment. In particular, the State of Idaho was considering cobble embeddedness as a stream criterion in Idaho water quality standards, and Burton and Harvey (1990) drafted a sampling procedure using the techniques developed by Skille and King (1989).

Like Burns (1984), Skille and King (1989) gathered comments from agency staff and incorporated them into the methodology. In July 1988, 20 USFS fisheries biologists and hydrologists united to review recent literature, share experiences, and refine methods. The discussions and streamside demonstrations resulted in a general consensus about standardization and application. The results of this effort were compiled into a draft methodology and sent to 33 hydrologists and fish biologists for review. Results of the standardization effort are paraphrased below, as are 1990 updates to the methods found only in agency correspondence documentation.

<u>Application Limits</u>

- Cobble embeddedness exhibits high spatial and temporal variability in both natural and disturbed streams. Sampling must be intensive within streams or stream reaches to detect changes (Potyondy 1988).
- Cobble embeddedness should be a measured parameter. However, visual or substrate surface assessments may be valuable for management needs.[17]
- Methods must be repeatable and not require extremely specialized training.
- Embeddedness measurements are most applicable in granitic watersheds or other geologies where sand is an important component of the annual sediment load and substrate. In basalts and other geologies where fines are predominantly silts and clays, low embeddedness values have high impact on fish (Chapman and McLeod 1987).[18]

[16] No guidance is given for situations where particles of the desired size range are exposed when extracting other particles. Care is needed to determine the plane of embeddedness and to avoid particles that are subsequently exposed below the plane of embeddedness.

[17] Presumably, this statement means that visual techniques may provide information for general characterization purposes.

[18] Impacts may be high despite low values of embeddedness in basalt geologies.

- Cobble embeddedness is best applied to streams where embeddedness levels are suspected or known to be limiting to salmonid rearing.
- Repeat monitoring must be conducted at the same site because of high instream variability (Munther and Frank 1986, Potyondy 1988).
- Application of the method in streams < 6.1 m (20 ft) wide may destroy sites for future monitoring (Potyondy 1988).
- Cobble embeddedness is most appropriate for stream-to-stream comparisons of similar reaches or for measuring temporal changes in the same reach.

Reach Selection Within Each Stream

- The reach should be representative of the channel system for which the study is addressed.
- The reach should be responsive to changes in sediment loads.
- Reach selection may differ depending on fish species and associated habitat importance. Appropriate fisheries expertise should be solicited in selecting sample reaches.
- Reach lengths should be at least 20 times the average stream width to ensure inclusion of all habitat types. Reaches should have an effective gradient of < 3 percent (reaches > than 3 percent are more transport-dominated and may not show depositional sediment trends).
- Additional measurements or observations should be made at embeddedness measurement sites to make data compatible with existing inventory databases and assist with data interpretation.

Transect Selection Within Each Reach

- Quantifying embeddedness in specific substrates (e.g., fish habitat units): Hoops can be tossed randomly within areas that are spatially homogeneous (Burns and Edwards 1985). However, to make inferences about an entire stream reach, all habitats within the reach must be included and represented in proportion to their distribution within that reach. A technique to randomize sampling throughout the reach is sampling on transect lines running from bank to bank. Beginning at the downstream end of a reach, the first transect is randomly located. Nine additional transects (for a total of 10) are uniformly spaced at intervals that are approximately twice the average channel width. This procedure will sample substrate types approximately proportional to their portion in the total reach length.
- When quantifying embeddedness for comparisons between reaches or between streams (above vs. below or treated vs. control), it is important to categorize similar reaches because differences in embeddedness between channel reaches may be partially explained by differences in channel type. Cross-sections should be surveyed for at least three transects (transects 1, 5, and 10) to determine the cross-sectional area, wetted perimeter, stream width, and average depth for existing low-flow and bankfull flow conditions.

Embeddedness Sample Selection Within Each Transect

- Three 60-cm-diameter hoop samples are randomly located in each transect (Figure 4). Within each hoop, all rocks

Figure 4. Random placement of hoops – BSK Method, South Fork Little Snake River, Colorado

between 4.5 and 30 cm are measured for embeddedness (fines are defined as particles less than 6.35 mm).[19]

Embeddedness Measurement

Depth of embeddedness (De) and total depth (Dt) are measured to the nearest mm perpendicular to the plane of embeddedness (Figure 2). The maximum length of the particle (Dm) is also measured (a-axis). For free matrix particles, those lying on the surface or not embedded by fines, the De is zero. The percent embeddedness of the hoop is $100*(\sum De/\sum Dt)$ (Table 2). This is an adaptation of the method developed by Burns and Edwards (1985), with some important differences: No surface velocity or depth criteria are used to locate samples, and each hoop is considered a sample. If depth over the hoop exceeds 45 cm (i.e., maximum depth that one can easily sample), a new random number is generated to relocate the hoop. If the hoop falls on rocks, logs, vegetation, or other debris that are above water, the sample site is relocated.

- Potyondy (1988) shows embeddedness calculated using 100*(S De/Dt)/n, and thus accounted for all particles sampled (Table 2). This calculation method was developed and is currently used on the Payette National Forest, McCall, Idaho. It accounts for free matrix particles, whereas the other method does not (De = 0 for free matrix particles). King stated that this method is a truer representation of available habitat and takes into account the size of the material.[20]
- Substrate exposed below the plane of embeddedness should not be measured.[21]
- A 1990 clarification[17] suggests that if gravels instead of fines (as defined) surround the particle, they should be removed until a "gasket" of appropriately sized fines is found where the plane of embeddedness is clear.[22]
- Any large rocks found in the hoop should be removed last so that other rocks are not disturbed.[18] If a boulder covers 25 percent of the hoop area, the hoop should be moved to another randomly located site on the same transect or moved 1 hoop length toward the thalweg.[23]
- If fines comprise more than 10 percent of a sample (with no rocks showing), a weighted embeddedness value is used for the hoop (Table 2), as recommended by Torquemada and Platts (1988). Ten percent is arbitrary, but this is a visual estimate, and accuracy finer than 10 percent is limited. The weighted value is calculated using the equation:

% weighted = (hoop area in fines (%) x 100 + remaining area (%) x % embeddedness)/100

[19] 1990 and 1991 modifications in the correspondence (see footnote 18) offer an alternative stating that the intermediate axis should be used for all size range criteria.

[20] Unpublished electronic correspondence between USFS hydrologists and Skille and King, EPA, 1990.

[21] However, one account states that all rocks accessible to macroinvertebrates and fry should be measured, but accessibility is difficult to determine.

[22] King [18] stated that this situation does not happen often, but it occurred many times in this analysis, which leaves the sample questionable because of different distinctions for fines made by different observers. If fines wash into the sample area, thus jeopardizing the sample, an upstream shield is used to block the stream current (Bunte and Abt 2001).

[23] Potyondy [18] stated that the hoop should never be moved without accounting for materials in each hoop. Otherwise, the technique fails to properly characterize the stream reach being sampled. Most informal references also note measuring the a-axis of the free matrix particles, then removing them before measuring the embedded particles. This is addressed in steps 7 and 8 of the Burns Method.

- Without weighting for fines, the method underestimates embeddedness. For example, if 50 percent of the hoop is fines and the cobble in the remaining 50 percent averages 40 percent embedded, the hoop embeddedness value would be 40 percent. Weighting gives the fines portion of the hoop a 100 percent embeddedness value and the cobble portion 40 percent or an average of 70 percent for the hoop.
- To aid in explaining special differences in embeddedness levels and to separate subsets of data for comparison with previous embeddedness measurements (e.g., studies confined to specific habitat types), the following measurements are made at each hoop: Surface velocity (flow meter or float); depth in center of hoop (or at upper and lower hoop edge depths (Torquemada and Platts1988)); percent surface fines (characterized as < 0.25 in.) in 10 percent categories; habitat type; distances from water's edge and thalweg; and comments on unusual conditions.

Determining Sample Size

- Using three sampled hoops at each of 10 transects provides for 30 samples per stream reach, which may or may not be enough depending on desired precision level. The following equation can be used to determine sample size (number of hoops):

  $n = t^2 s^2/E^2$

  where

  n = sample number
  t = Student's t
  s = standard deviation
  E = precision level

- For example, after sampling 30 hoops the observer determined that the standard deviation for embeddedness was 11.5. (To determine whether sample size is adequate to be within ±5 percent of the true embeddedness value, and assuming you can accept being wrong 1 in 20 times, you would set alpha = 0.05; determine a Student's *t* of 2.042 for 30 degrees of freedom, and then calculate *n* as 22.05.) Thus, 22 or 23 samples would have been adequate, and no additional samples would have been needed. Sample size can be calculated after taking any number of samples.
- If the objective is to quantify embeddedness in a specific substrate or habitat type, "n" samples must be collected and sampling must proceed until the required number of hoops fall on that particular habitat type. When the sample size required to characterize the reach has been met, then only hoops landing in the particular habitat type of interest need to be sampled.[24]

Data Interpretation

- Cobble embeddedness is usually expressed as a percentage. However, this value does not reflect the amount of exposed rock, which is the critical component of the habitat for aquatic organisms. Cobble embeddedness expressed as a percent is not as sensitive to changes in sediment over time. Rocks that become completely buried in sediment are no longer part of the measurable population. Consequently, the lost "living space" is not reflected in the percent embeddedness figure.
- When the objective is to monitor changes in stream sediment over time, it is better to calculate the amount of vertically exposed rock

[24] Time to measure three hoops can vary from 20 to 45 minutes, depending on substrate composition. One day is typically required for a two-person crew to gather data for one sample set.

(∑(Dt-De)). This "living space"[25] and embeddedness can be calculated from the same field measurements. The choice may depend on the study objectives (e.g., evaluating fish or insect habitat) and whether changes over time or differences between streams are being determined. Preliminary evaluation of the vertically exposed rock parameter indicates that it also has a good correlation with the percentage and number of free matrix particles.

Free Matrix Particles

- The percentage of the number of measured rocks that are free matrix particles has been shown to have an inverse correlation with the percentage of embeddedness (i.e., large numbers of free matrix particles imply low embeddedness) (Burns and Edwards 1985, Munther and Frank 1986, Potyondy 1988, Torquemada and Platts 1988). Because fine material is not counted in the free matrix estimates, a weak correlation exists when using the weighted embeddedness calculation technique (Torquemada and Platts 1988).
- With continued sampling of the same stream or similar streams in the same drainage, it may be possible to develop a double sampling scheme requiring less field time. Such a sampling scheme would rely on determining the percentage of free matrix particles within a hoop at most sampling points, with a subsample of hoops also being measured for embeddedness. This method is employed on the Payette National Forest at sites where only the free matrix method is used. [3]

Skille and King (1989) pointed out that forest hydrologists and fish biologists often have different objectives for stream evaluations and often work in a wide range of watershed and geologic conditions. Skille and King (1989) stated that sampling schemes should be flexible to address different objectives. For example, monitoring programs that address the effects of sediment on fish may be based on sampling of pre-selected habitat types. Temporal changes in stream sediment may be monitored by the change in a selected reach over several years. If inferences are to be made about entire stream systems, then several replications of reaches must be sampled. Embeddedness is only one measure of habitat condition; other habitat parameters should be concurrently measured in most cases. The techniques discussed herein were structured for Idaho DEQ, IDEQ's Best Management Practices (BMP) monitoring plans, and the USFS's water quality monitoring plans. Flexibility is allowed to meet specific objectives yet retain a degree of standardization.

USFWS – Upper Colorado River Measurement Method

This method fundamentally differs from the others. It quantifies embeddedness by measuring the "depth to embeddedness" from the top of rocks sampled. Paraphrasing from Osmundson and Scheer (1998), this technique was developed to monitor embeddedness of gravel and cobble substrates in the upper Colorado River. Twenty measurements were taken at 15 sites during the descending limb of the spring hydrograph and for summer and fall base flows. The study reaches corresponded to food-availability study areas and convenient access.

Each sampling effort was conducted during one 8-hr workday by a team of two people. Within each study reach, a minimum of one run and one riffle was sampled. Shoreline and thalweg portions of the reach were not sampled because of excessive depositions of fines and high water depth. Water depth and velocity were recorded. Sample locations were modified for each sampling effort corresponding to the different flow levels to maintain consistent depth and velocity environs.

The technique consists of first laying one hand flat on top of the cobble surface layer. Holding the other hand perpendicular to the first, the fingers are extended down between the thumb and forefinger of the first hand until the tip of the index finger reaches the layer of embeddedness. Rocks adjacent to the selected rock are pushed aside before the

[25] "Living space" describes the spaces between substrates that are available habitat and cover for small fish or other aquatic life.

embeddedness layer is located. The embeddedness layer is identified when more than a moderate effort was necessary to push the middle finger deeper into the substrate. Twenty measurements of embeddedness are taken per site. Having each person measure half of the samples at each site helps to minimize bias from differences in observer technique. Each observer wades parallel to the shore and takes a measurement every two steps. While placing the hand on top of the rocks, the observer looks in a forward direction to minimize placement biases that might result if the substrate is viewed during hand placement.

Embeddedness measurements are averaged and means are compared among sites and among dates within sites. The technique also describes the DTE in terms of the number of rocks above the embeddedness layer (free rocks or relative DTE). Each of the 20 DTE measurements are divided by the median rock width (Wolman 1954) for that site and then averaged. This effort allows a measure of variability around the mean number of free rocks.[26]

USGS NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Fitzpatrick et al. (1998) used the same definition as Platts, Megahan, and Minshall (1983) and quoted what this analysis has determined as a misprint in Platts, Megahan, and Minshall (1983) (i.e., when the percentage of embeddedness is said to decrease, the biotic productivity also decreases. The relationship is actually inverse under the current status of embeddedness measurement.[1] The protocol provided by Fitzpatrick et al. (1998) is also unique to other publications and methods. The following guidance is offered:

> *Embeddedness is estimated by determining the percentage of the surface area of the larger-sized particles (by visual estimation) covered by fine sediment. Five relatively large (gravel-to-boulder size) substrate particles are examined at the three transect points. The percentage (to the nearest 10 percent) of each particle's height that was buried in sediment is noted by the extent of discoloration of the particle surface. The percentage of fine sediment covering the large substrate particles is determined from calculating the average percentage of coverage for the five particles. In turbid wadeable reaches and in nonwadeable reaches, a sample of the substrate may be obtained by use of a shovel, Ponar sampler, or Ekman dredge, but data from nonwadeable reaches are not required for NAWQA national data aggregation.*

EMBEDDEDNESS STUDIES

Studies Prior to 1987

Burns (1984) sampled embeddedness in 19 tributaries of the South Fork of the Salmon River with varying levels of development. He found that streams with more development had statistically significant higher mean embeddedness than undeveloped or partially developed streams. Partially developed and undeveloped streams were not significantly different from each other. Regression analysis of fine sediment from core samples (Corely and Newberry 1982, Lund 1982) versus mean embeddedness for 11 sites showed significant correlation ($r^2 = 0.63$, $p = 0.01$).[27] Each regressed data point represented a mean derived from 40 core samples and at least 100 individual rock embeddedness measurements.

Burns (1984) also regressed the relative frequency of free matrix particles against mean embeddedness and found a significant relationship ($r^2 = 0.82$, $p = 0.01$). Burns (1984) defined a "free" particle as one not surrounded by either fines or very fine gravel and found that no rocks were free at 45 percent embeddedness. At 0 percent embeddedness, 85 percent of rocks were free. Consequently, Burns and Edwards (1985) suggested that free

[26] This method is probably best utilized for measuring a specific site over time, rather than for drawing conclusions between sites, because the DTE will depend on the particle distribution of the site.

[27] This is a comparison of spawning gravel and rearing habitat.

matrix particles might offer a more sensitive measure than embeddedness when embeddedness values range from 0 to 50 percent.

Burns (1984) did not address temporal changes or variation of embeddedness measures within a sample site. Kramer (1989) concluded that the embeddedness methodology is "flawed" and does not accurately address temporal change (see following section). Burns (1984) stated that the embeddedness methodology did not work well in basalt parent material because clays and silts are easily moved and armoring is more pronounced; the technique is more appropriate where sand is an important substrate component. Klamt (1976), Kelley and Dettman (1980), and Burns (1984) intended embeddedness measures to pertain to habitat suited for rearing or winter refuge rather than for spawning gravels. In severely armored surfaces, percentages of free particles may offer useful ancillary measures of substrate condition for winter refuge.

When Burns (1984) measured embeddedness in spawning areas, water depths were always greater than 30 cm, core sampling had not disturbed the sites, spawning had already occurred at the site, and the hoop was moved if particles were outside the defined range (4.5 - 30 cm). Samples were avoided where the hoop was in the eddy of a pool or large boulders. Burns (1984) stated that it might be impossible to obtain suitable measures of embeddedness in streams with numerous boulders.

Burns (1984) and Burns and Edwards (1985) assessed changes in mean embeddedness due to development and found that a tributary, Mule Creek, contributed to downstream habitat degradation of Monumental Creek. They also reported that Boulder Creek, a tributary of the Little Salmon River, had high embeddedness immediately downstream from logging and road construction relative to an upstream control area (42 and 20 percent embeddedness, respectively). Kelley and Dettman (1980) found embeddedness to be a useful measure of substrate character in Lagunitas Creek, California. They visually estimated percent embeddedness on particles larger than 45 mm in diameter and stratified habitats to reduce variability, as suggested by Burns and Edwards (1985).

Munther and Frank (1986) quantified conditions in Montana streams and noted that excavation below the surface layer is commonly needed to reach the substrate level that is embedded. They removed all free matrix particles from the area of the sample hoop and then measured all embedded substrates. Positive correlations were found between embeddedness and core-sampled fines larger than 0.21 mm and smaller than 0.84 mm (r^2 = 0.55 and 0.73). Free matrix particles were negatively correlated to fines (r^2 = 0.73 and 0.90). Significant differences (alpha at 0.01 or 0.05 levels) existed in 4 of 8 pairings of habitat units (riffles, tailouts, and runs) between developed and undeveloped streams.

In 1987 the Bonneville Power Administration funded a 2-year project to design and collect baseline data for a 10-year monitoring study of potential effects on fishery resources in the Coeur d'Alene and Hayden Creek watersheds from the construction of a BPA 500-kV power line. The assessment consisted of embeddedness measurements at 61 stream locations using the method described by Burns (1984). This technique measured a minimum of 100 large substrate particles and quantified results using mean percent embeddedness and percent free matrix particles. The study found wide ranges of embeddedness among streams and an inverse relationship between percent embeddedness and percent free matrix particles. However, a strong relationship between embeddedness and trout densities was absent (r^2 = 0.12; p>0.05), with an insignificant relationship between free matrix particles and trout densities (r^2 = 0.11; p> 0.05).

Kramer (1989)

Kramer (1989) identified several limitations to embeddedness methodology, concluding that the techniques developed by Burns (1984) and Skille and King (1989) failed to accurately portray the true nature of temporal sediment changes in a channel. Kramer (1989) simulated conditions where fine sediment levels were increased and found that percent

embeddedness actually decreased with increasing fine materials. This occurred because rocks that became 100 percent embedded were no longer measured; i.e., the total rock count was reduced and calculated percent embeddedness of the sample decreased (Figure 5). Kramer (1989) also questioned critical statistical assumptions. Specifically, individual rocks confined to a given area cannot be quantified individually because rocks adjacent to each other have related values and do not act independently. Rocks in each area, subjected to similar hydrologic and hydraulic conditions, should be treated as one unit.

Kramer (1989) proposed an alternative indexing technique and coined the term "interstitial space index (ISI)." For each rock of suitable size within the hoop, Kramer (1989) suggested measuring the height of the rock

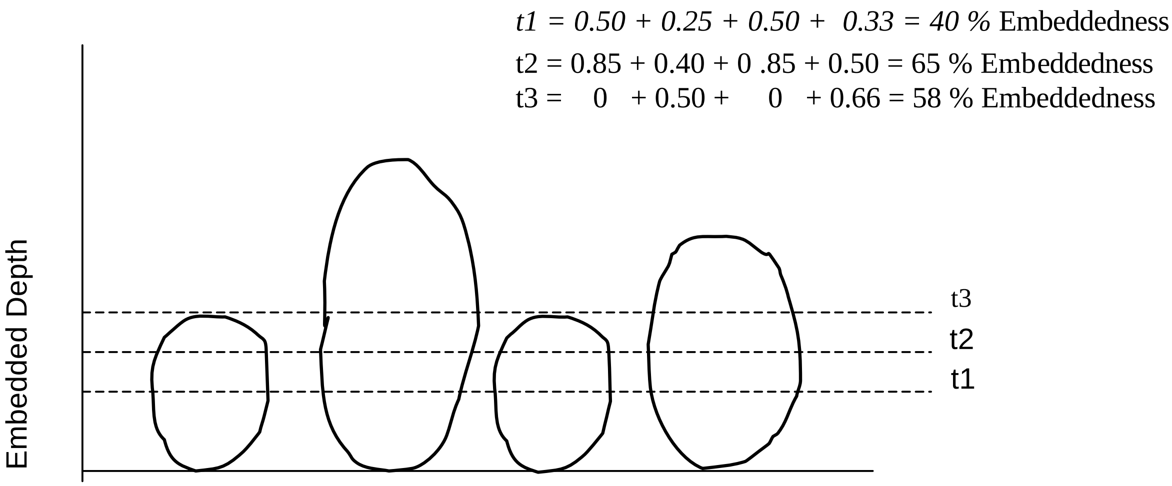

Figure 5. Simulated embeddedness increases that result in a reduction of calculated embeddedness

perpendicular to the plane of embeddedness that is not surrounded by fine sediment (i.e., analogous to protrusion or "DTE" in typical embeddedness measurements). All protrusion heights, DTE, of individual rocks within the hoop are summed and then divided by the hoop area (e.g., isi = ? DTE/A). A resultant value (units of m/m^2) is determined by averaging each hoop "isi" by the total number of hoops (N) in the subject reach (e.g., ISI = ? isi/N).

The ISI is an improvement over percent cobble embeddedness because the ISI will continually decrease with increases in fine sediment; however, the measure is sensitive to particle size distribution (Kramer 1989). A change in ISI between years may result from either fine sediment quantity or particle size distribution changes. Furthermore, the ISI provides information on the vertical axis but does not compensate for differences in the cross-sectional area of the rock. In other words, a low ISI could result from either a few tightly packed large rocks or many scattered small rocks surrounded by fine sediment. Consequently, Kramer (1989) suggested comparing size distribution of each sample as the only meaningful way to monitor between years.

Ries and Burns (1989)

Using the Burns Method (Burns and Edwards 1985), Ries and Burns (1989) conducted a study on embeddedness of salmon habitat in selected streams on the Payette National Forest in Idaho. No obvious trends in control locations were found from 1987 through 1988, but Ries and Burns (1989) noted apparently improving trends in two of the developed watersheds. In another watershed, no trends were found. Free matrix particles were strongly correlated with embeddedness. Free matrix sampling was found to take longer than conducting the embeddedness measurements

because more rocks were required for an adequate sample, thus increasing sampling time for all typical measurements made at each site. Cluster analysis also showed distinctions between geologies. Relationships between depth and velocity and embeddedness were inconclusive. Free matrix particles increased with stream order, whereas embeddedness decreased. Year-to-year variations of flushing flows and summer thundershowers probably strongly influence particle embeddedness. This likely hinders interpretation of data so that only general long-term trends are discernible. According to Ries and Burns (1989), a stratified sampling approach would reduce confounding variables, and further monitoring should be designed to refine these issues.

Potyondy (1993)

Potyondy (1993) summarized the results of cobble embeddedness analyses conducted on 120 streams in the Idaho Batholith on the Boise National Forest (Potyondy 1988). Potyondy (1993) condensed the study conducted in 1988 and focused on cobble embeddedness as it relates to beneficial use protection in Idaho. Specifically, the study addressed the effectiveness of embeddedness as a measure of fish habitat condition in relation to land management activities. It is one of the most rigorous of all embeddedness studies and used the Burns (1984) measurement methodology. Potyondy found no statistical differences among streams in watersheds with various degrees of land-disturbing impacts attributed to timber harvest, road construction, grazing, and mining. Stream embeddedness levels appeared to be more closely related to estimated natural sediment yields related to geology rather than to management activities occurring in the watersheds.

A subset of seven least impacted and seven most impacted watersheds was selected from the 120 total watersheds; selections were based on road densities and modeled sediment yield increases. (Road densities in the seven most impacted watersheds averaged 7.3 km of road per 2.6 km^2 (4.5 miles per mile^2) – an average 15 times greater than in the least developed watersheds with an average of 0.48 km per 2.6 km^2 (0.3 mile per mile^2). The average modeled sediment yield increase over natural levels was 91 times greater in the developed watersheds than in the least developed watersheds. Cobble embeddedness means of the 14 streams were tested for statistical difference at the 0.05 percent significance level. Embeddedness levels in the most-developed watersheds were not statistically different from embeddedness levels in the least-developed watersheds.

Potyondy (1993) concluded that events within the watershed are not necessarily reflected in the stream because of the complexity of processes involved. Impacts of sediment on fish are influenced by both sediment availability and routing within the channel system. Many of these processes are poorly understood and may significantly influence embeddedness levels.

Potyondy (1993) cautioned that the results of this analysis should not be misconstrued to mean that land-management impacts could not be detected using cobble embeddedness measurements. Embeddedness measurements may reflect temporal changes when repeated measurements are made immediately below major land-disturbing activities. However, detection of statistically significant change will be difficult when activities are widely dispersed, as is often the case with non-point sources, or when the degree of impact is relatively minor.

Embeddedness data and interpretation must account for natural watershed characteristics in addition to management-induced impacts. Potyondy (1993) concluded that it does not currently appear advisable to assign numerical standards for regulatory purposes or to develop instream threshold of cobble embeddedness in land management planning. Carefully controlled research studies are needed to further explore the utility of the embeddedness methodology.

Gerhardt and Green (1991) used embeddedness to monitor 3 years of stream response to fire on East Moose Creek, Nez Perce National Forest. Each year 16 samples were collected with two hoops per transect. No significant difference was found between years.

Torquemada (1993)

Torquemada (1993) compared streambed-monitoring techniques in chinook salmon spawning and rearing areas and reported that measured embeddedness (using the hoop method)[28] was a poor indicator of ocular surface composition and quality of the overall site. After modifying the "hoop" technique by reducing the hoop size to 30 cm and including particles as small as 1 cm, Torquemada (1993) found significant correlations between surface composition and visual embeddedness estimates. Experienced observers obtained similar results in both ocular and measured bias trials. Untrained observers obtained similar results in measured trials but not in ocular trials. Torquemada (1993) concluded that the use of ocular techniques as water quality criteria for assessing compliance with non-point source pollution standards would require extensive quality control and certification measures.[29]

Nelson et al. (1997)

This report consolidated sediment monitoring data on the Payette National Forest from 1977 to 1996 (with some sites that are on the Boise National Forest at Cabin Creek and Goat Creek where the South Fork Salmon River road intersects both National Forests.[3] Nelson et al. (1997) reported that trends in surface and interstitial sediment monitoring are less clear than subsurface core sampling results, but results were more descriptive with respect to sediment conditions throughout the watershed. Several studies indicated that heavily developed watersheds generally had more highly embedded cobbles and fewer free cobbles than their respective controls; however, the difference was sometimes small, and the control sites were not always in totally undeveloped watersheds.

A smaller sample of studies indicated few trends in surface/interstitial sediment conditions, with some of the trends indicating an increase in fine sediment in undeveloped sites. Some measurements of cobble embeddedness in undeveloped watersheds failed to meet specific cobble embeddedness objectives identified in the planning guidance on the Payette National Forest. These results have previously been reported and suggest that sediment conditions, even in the absence of development, are highly variable.

Nelson et al. (1997) found that questionable embeddedness data had led to confusion with respect to compliance with the Forest Plan. Core sampling and 30-hoop free matrix techniques were considered the most reliable (specific techniques not identified). Nelson et al. (1997) believed that embeddedness might be just as reliable even though quality of measurements from 1991 to 1995 had significantly increased the uncertainty of the embeddedness data (e.g., regression relationships were inconsistent with past studies and inadequate crew training led to improper techniques). The report concluded with tentative revisions to specific sediment objectives for streams in granitic watersheds. New guidelines are less restrictive and more consistent with natural streams, which appear to have an average 35 percent embeddedness. Recommendations pertained to continued implementation of the sediment-monitoring program. Investigation of technique efficacy is ongoing, as efforts focus on improving reliability while reducing annual monitoring expenses.

U.S. Fish and Wildlife Service – Upper Colorado River (1998)

In 1998 the USFWS began a baseline study to monitor embeddedness of gravel and cobble substrates in the upper Colorado River. This embeddedness method is fundamentally different from others. Little research involving effects of sedimentation on stream communities has been conducted on the upper Colorado River, which is inhabited by the endangered Colorado squawfish (*Ptychocheilus lucius*). Flow regulation in the headwaters has reduced the frequency of flows capable of mobilizing the armor layer (thus winnowing fine materials from gravel and cobble substrates) in reaches occupied by the Colorado squawfish (Osmundson and Kaeding 1991, Van Steeter and Pitlick 1998). Riffles had slightly greater depths to embeddedness

[28] No specific criteria are given. The method is most likely the Burns (1984) method.

[29] Torquemada (1993) expanded the study site from a habitat unit to a larger area and noted that large amounts of fines were a confounding problem.[3] Nelson states that in the Burns (1984) and Burns and Edwards (1985) methods, the stratification prevents the problem Torquemada encountered.

than runs. Depths to embeddedness were similar between reaches and between runoff and base-flow periods. Depth to embeddedness (Burns Method) remained fairly constant through the base-flow period, and both reaches sampled were freshly cleaned of fine sediment.

CURRENT APPLICATION

Few field projects currently use the BSK method even though it is featured in MacDonald, Smart, and Wissmar (1991); Bunte and Abt (2001); and Gebhards (2002). The method was widely used by the Payette, Boise, Nez Perce, Clearwater, Helena, Deerlodge, Bitterroot, and Lolo National Forests in the late 1980s and early 1990s. Harvey (1989) and Burton and Harvey (1990) developed percent embeddedness as a criterion in Idaho Water Quality Standards and protocols, but embeddedness does not appear in recent Idaho DEQ documents.

Table 4 summarizes use of embeddedness indices in the United States from 1997 to 2001. This list, although not exhaustive, indicates that embeddedness remains a common monitoring technique and is present as a water quality criterion where legal implications, such as Total Maximum Daily Load (TMDL) issues, may ensue. Table 4 also identifies the non-standardized nature of the methodology (i.e., several original or modified versions exist). Although the technique was primarily developed in Idaho, with fairly substantial development and use in Montana in the late 1980s and early 1990s, its use as a water quality or BMP criterion has largely been discontinued in both states.

Table 4. Current Use of Embeddedness.

*State	Use	Date	Embeddedness Method
Alaska	Alaska Department of Fish and Game Chester Creek Stream Condition Evaluation	2001	Local Method -- Measured w/ Wolman Pebble Counts
Arizona	Arizona Department of Environmental Quality – WQD: Assessment and Monitoring	2001	Patti Spindler (602) 207-4543
California	North Coast Region Water Quality Control Board -- Update recommendations to 303(d) list (embeddedness ratings)	2001	Local CDFG method
Colorado	--U.S. Fish & Wildlife Service – Upper Colorado River Study (Osmundson and Scheer 1998) --Colorado Department of Public Health and Environment Water Quality Control Commission --- Provisional Implementation Guidance for Determining Sediment Deposition Impacts to Aquatic Life in Streams and Rivers -- Surface Water Assessment -- Colorado State University – Little Snake River Assessment	1998 1998 2000 2001	Local method Platts et al. 1983 Not identified Platts et al. 1983
Idaho	Several past documents, but no new DEQ assessments or criterion. USFS timber sale appeals on Clearwater National Forests	1999	Not identified
Indiana	-- City of Anderson – Parks and Recreation Department Preliminary Diagnostic Study of Anderson Park Lakes -- Impact of TMDLs on Surface Water Quality Monitoring Strategy	1999 2001	Qualitative description Not Identified

Table 4 (cont.). Current Use of Embeddedness.

*State	Use	Date	Embeddedness Method
Kentucky	Kentucky Division of Water – studies, guidelines, and volunteer programs	2001	EPA Methods
Massachu-setts	Commonwealth of Massachusetts Department of Environmental Protection - Charles River Watershed Water Quality Assessment - Numerous other basin assessments	1997 2001	Not identified
Missouri	State DEQ - TMDL Implementation strategies – instream criterion for maximum allowable percent embeddedness of coarse substrate by sand or finer-sized particles. The criterion would be evaluated at riffles within a designated range of flow velocities.	2001	Not identified
New Hampshire	Department of Environmental Services -- Watershed Management Bureau Biomonitoring Program	2001	Klamt 1976
New Mexico	State Water Quality Standards --Draft TMDL for Jemez Watershed	1999	BSK
Oregon	Draft Stream Macroinvertebrate Protocol – Oregon Plan for Salmon and Watersheds – Water Quality Interagency Workgroup	1998	EPA Rapid Bioassessment
Pennsyl-vania	Division of Water Quality Assessment and Standards – Stream Redesignation Evaluation Report - Numerous other habitat assessments	2001	Not identified
Vermont	Water Quality Division Biomonitoring and Aquatic Studies Section	2001	Platts et al. 1983
Washington	Aquatic Field Protocols Adopted by the Fish, Farm, and Forest Communities Technical Committee – measure and record embeddedness in all pool habitat	1997	Unclear
Wisconsin	Department of Environmental Resources -- East Branch Rock River Watershed Assessment -- three other documents	1999	Klamt 1976

*Data found from American Water Works Association Website.

The Payette National Forest in Idaho is currently performing a technique termed the "30-hoop free matrix." Use of this technique began in 1988. It is a reach-based approach that has been found to correlate with embeddedness.[30] Embeddedness is monitored annually; but more sites are evaluated with the free matrix technique, and embeddedness is estimated at the sites with only free matrix counts (double sampling - see "Data Interpretation" subsection).[3]

SUMMARY

Substrate Selection

Visual methods and the USFWS method on the upper Colorado River measure embeddedness

[30] Personal communication, 20 October 2001, Mr. Rodger Nelson, Fisheries Biologist, Payette National Forest, McCall, ID.

of the stream pavement. The BSK method measures a combination of pavement and subpavement substrates. Comparability between measures is therefore highly questionable.

- The BSK method measures particles in the hoop from 4.5 to 30 cm.
- Torquemada and Platts (1988) modified the BSK method to include particles as small as 1 cm.
- EPA EMAP measures all substrate, regardless of size.
- Platts, Megahan, and Minshall (1983) measures gravel-, rubble-, and cobble-sized particles.

Site Selection

Fish habitat units are not easy to define. Variance exists between units and between observers selecting units. Munther and Frank (1986) found no significant difference between riffles, pool tailouts, and intermediate zones. Potyondy (1988), as well as Munther and Lilburn (1986), concluded that temporal measurement must be conducted at the same site because of high instream variability; for streams less than 6 m (20 ft) wide, sites meeting measurement criteria are difficult to find. Once sampled, the substrate is destroyed for future monitoring.

- Platts, Megahan, and Minshall (1983) did not mention specific sites but stated that the visual technique allows for determining the substrate suitability for spawning, egg incubation, habitats for aquatic insects, and young overwintering fish.
- The BSK method was not developed to assess spawning gravels (Chapman and McLeod 1987)
- Burns (1984) looked at specific fish habitat units, whereas Skille and King (1989) applied the method to channel transects.
- King measured slow and fast water habitats (pools and riffles) (Skille and King 1989).
- Potyondy (1988) sampled sites meeting the velocity and depth criteria established by Burns (1984).
- EPA EMAP procedures specified a representative reach and 11 similar transects in the reach (i.e., sample a variety of habitat units).
- The upper Colorado River assessment samples one run and one riffle for each study reach.

Geology

Only the BSK development discussed geology. The following variations can be found in the literature.

- Sand must be an important component of the substrate (Burns and Edwards 1985, Potyondy 1988).
- Fines in basalt areas are clays and silts, and armoring is common (low embeddedness may still mean high impact to fish habitat) (Chapman 1988).
- Where sand is prevalent, the method underestimates embeddedness (Torquemada 1993).[31]
- Watersheds in the Idaho Batholith with as much as 40 percent basalt still have enough granitic sand to behave as granitic streams for the purpose of embeddedness measurements (Potyondy 1988).

Water Criteria

The upper Colorado River study discussed measurement on the descending limb of the hydrograph and during summer and fall base flow conditions. The study avoided the thalweg because of excessive water depths and recorded water velocity and depth for duplication in repeated surveys. The following variations exist for the BSK Method:

- Surface velocity of 24 – 66.7 cm/sec (Burns 1984, Torquemada 1993).
- Float time across hoop = 0.9 – 2.5 sec (Potyondy 1988).
- Slow water/fast water.[17]

[31] Torquemada may have felt that this technique underestimated embeddedness because it did not account for large areas within a hoop that were covered by fines.[3] Nelson stated that this could occur in habitats for which the Burns Method was not intended and that it is unlikely to be an issue if the protocol is followed correctly. However, more research in a variety of habitats is necessary to substantiate this observation.

- Water depth not less than 15 cm or more than 45 cm.[17]
- Hoop must fall where bank deposition is not obvious and where no part of the hoop lies in an eddy (Munther and Frank 1986).

Sample Size

Platts, Megahan, and Minshall (1983) did not address sample size. Bain and Stevenson (1999) recommended five measurements in each habitat unit. EPA Methodology results in 55 samples; 5 at 11 representative transects. Skille and King (1989) listed the following variations for the BSK Method:

- A 60-cm hoop defines the sample area.
- Rocks are usually considered samples, and sampling is continued until at least 100 cobbles are measured.
- All suitable particles are measured in the last hoop, even if 100 are exceeded.
- Two cobble embeddedness measurements are taken at each stream reach (Potyondy 1988). (An embeddedness measurement was the average of measured substrates in one hoop.)
- King[17] considered each hoop to be a sample.
- Burns (1984) estimated that 100 particles could detect a cobble embeddedness difference of 12 to 18 percent and that 400 particles would be needed to assess a 5-percent difference.

Use of Free Matrix Particles

Burns (1984) suggested that free matrix particles might offer a measure more sensitive than embeddedness percentages in conditions from 0 to 50 percent embeddedness. Munther and Lilburn (1988), Potyondy (1988), and Torquemada (1993) found significant correlation between percent cobble embeddedness and percent free matrix. Potyondy (1988) suggested simplifying the sampling technique to a system by tallying free matrix particles, assuming that errors on the order of ±7 percent are acceptable. (Some studies correlated number of free matrix rocks; others used a percentage of the embedded measured rocks. Strictly interpreting the original definition, percent free matrix is a proportion of the total measured rocks.)

Fundamental Concerns

All methods measure embeddedness by depth of embeddedness except the Upper Colorado River study (Osmundson and Scheer 1998), which measures embeddedness as the “depth to embeddedness.” Results from the Boise National Forest annual summary, Potyondy (1988), and computer simulations by Kramer (1989) found that increased sedimentation can result in decreased embeddedness. Kramer (1989) found no use for the methodology because of this “flaw.”

Although embeddedness is still widely used as a substrate measurement, certain negative aspects are apparent. These include the following:

- Large differences exist in methodologies.
- Published guidance does not provide the appropriate detail needed for field application.
- Fundamental defects may indicate that an entire change in approach is necessary.
- Studies show why Idaho DEQ and USFS Regions have largely discontinued use of the measured embeddedness method as a monitoring technique. Without additional research addressing the reliability of embeddedness outputs from the assorted methods, use of embeddedness in standards and guidelines or linking embeddedness to biologic criteria currently appears highly questionable.

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